Introduction to Radiative Heating

Brett A. Cruden
AMA Inc. at NASA Ames Research Center

Ames/Langley Summer Seminar Series
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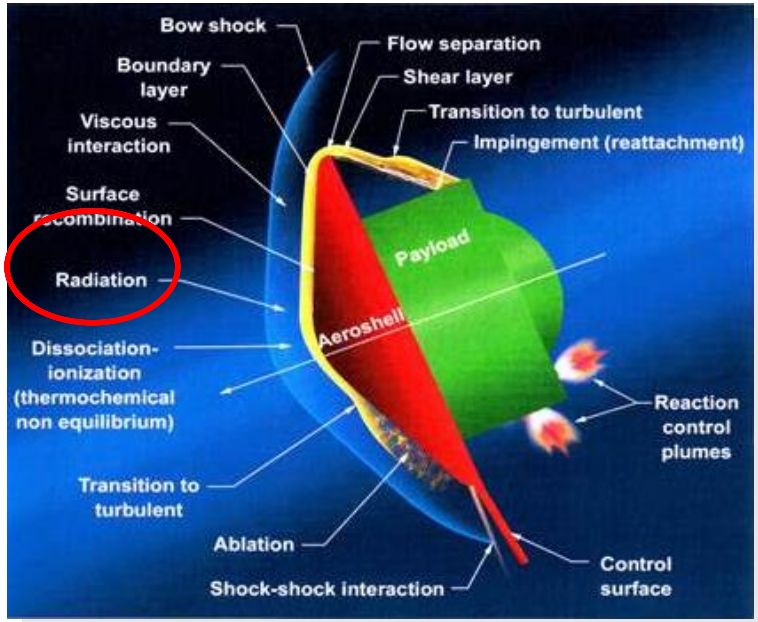
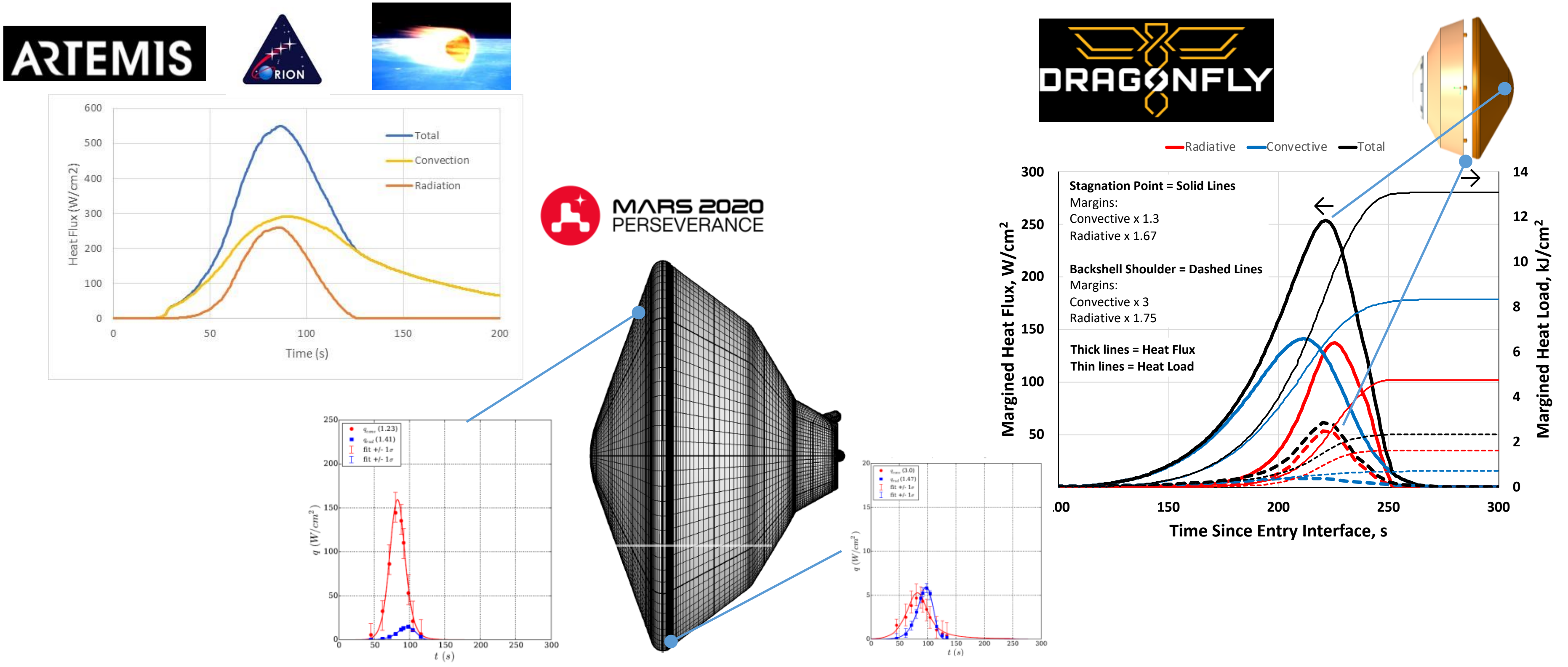
Radiation in Planetary Entry Aeroheating



- Spacecraft kinetic energy is converted to thermal energy during atmospheric entry deceleration
- Thermal energy must be absorbed/dissipated by thermal protection system (TPS)
- Part of that thermal energy reaches spacecraft through convective and radiative heat transfer
  - Radiative heating scales as $\rho r_n V^8$, in blackbody limit
  - Becomes relevant for large vehicles and/or high entry velocities
- Recent studies have found exceptions to the above
  - Radiative heating often larger on the backshell than convection
  - Regimes of molecular radiation occur at intermediate velocities, may cause non-monotonic radiation wrt V
- Phenomenological models of shock radiation are used in CFD simulation tools to assess impact of radiative heating
  - Models are developed and validated through ground testing (and flight test data, if available)

Radiation, in Mission Context

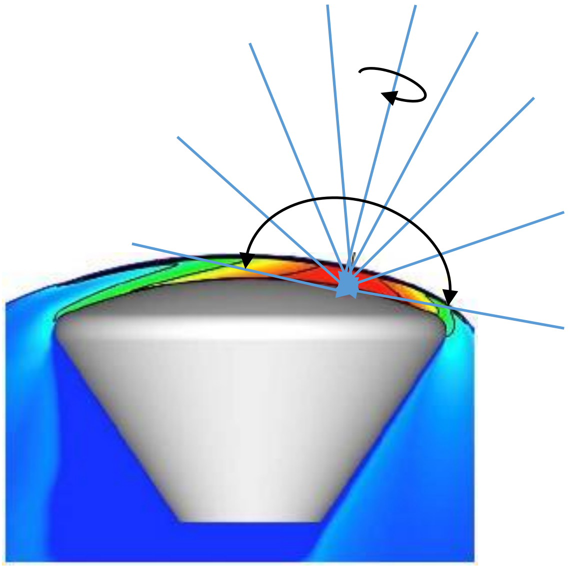


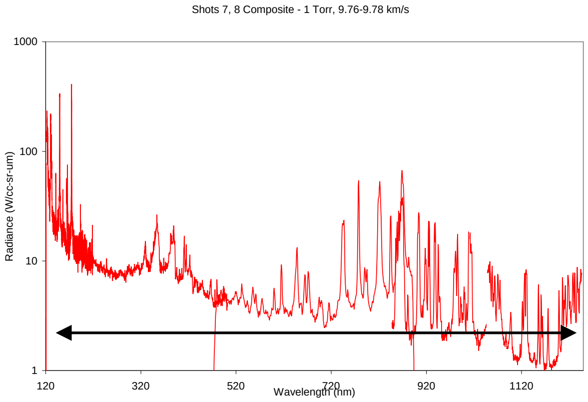
- Radiation is significant form of heating for many missions
  - Often dominant on backshell or at high velocity

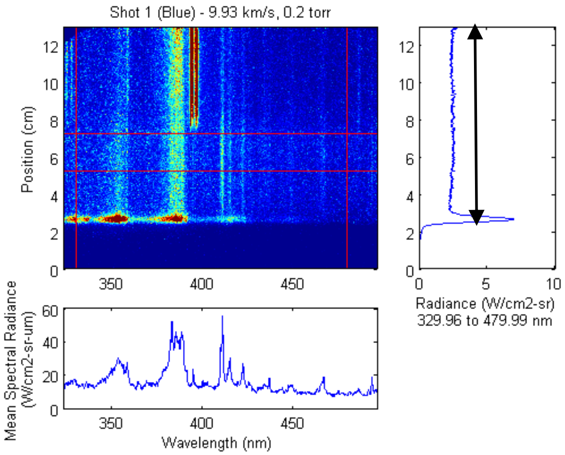
Basic Radiation Terminology

- **Radiative Heat Flux** is equal to the:
  - **Irradiance,** which is the integral of the:
    - **Radiance,** which is the integral of the:
      - **Spectral Radiance,** which is the integral of the:
        - **Volumetric Spectral Radiance**

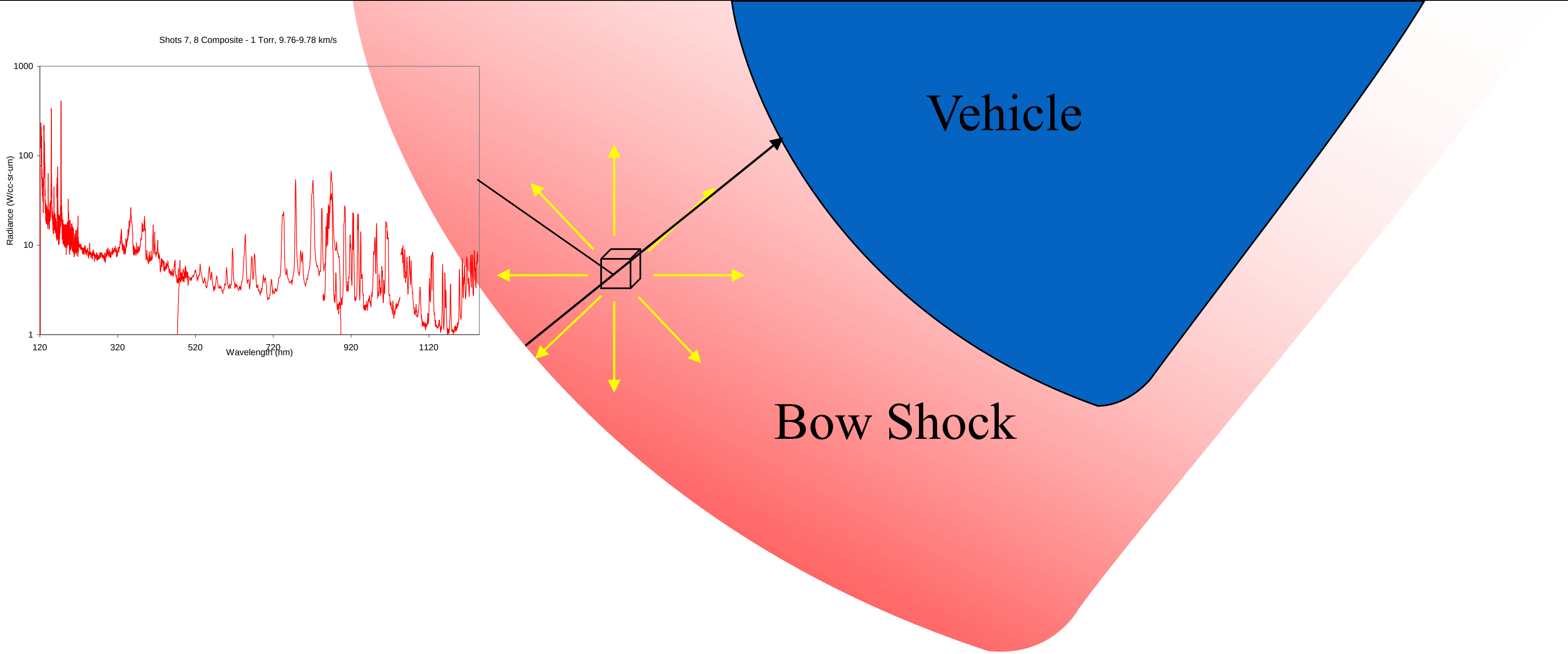
kinda







Volumetric Spectral Radiance

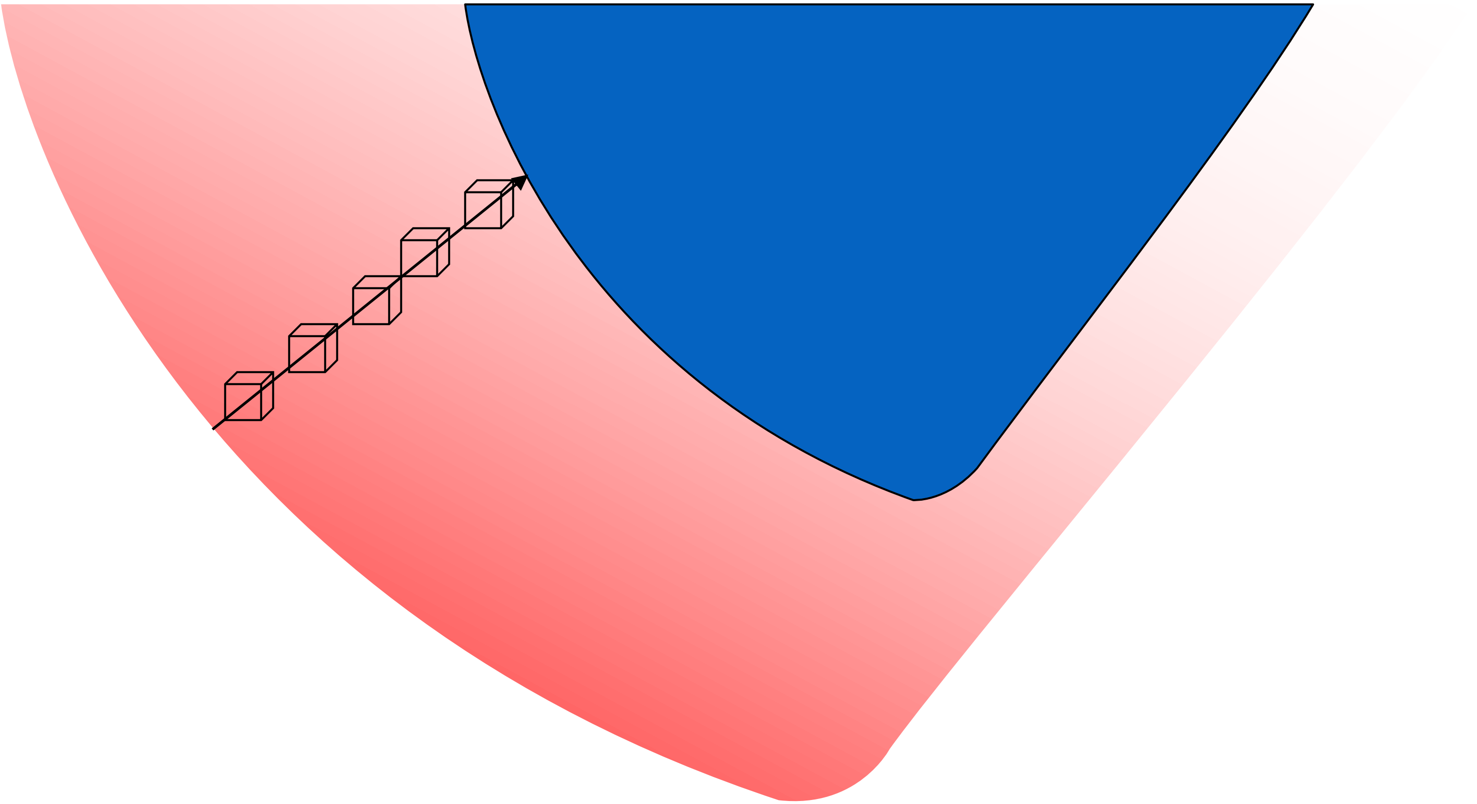


- In the bow shock, a control volume radiates uniformly in all directions
- The radiation has a spectral (wavelength dependent) signature
- The surface "sees" the volume through its intersecting line of sight
- The fundamental quantity then is the *volumetric spectral radiance*, e_λ

  Power per Wavelength per Volume per Solid Angle (W/cm^3-sr-μm)

  (Also known as an *emission coefficient*)

The Radiation is accumulated over a line of sight



- A radiating *Line of Sight* passes through multiple control volumes, all of which absorb and radiate light. The surface sees the integral along this line of sight:

$$L_\lambda(\lambda, L) = \int_0^L \left(e_\lambda(\lambda, x) - a_\lambda(\lambda, x) L_\lambda(\lambda, x)\right) dx$$

- At equilibrium, the *absorption coefficient* is related to the emission coefficient by *Planck's function*:

$$a_\lambda(\lambda, x) = \frac{e_\lambda(\lambda, x)}{B_\lambda(\lambda, T(x))}$$

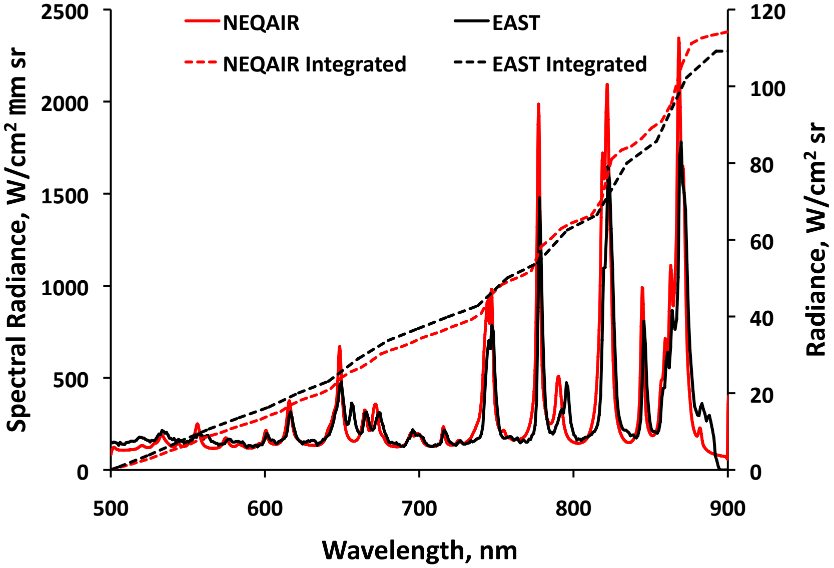
- For *optically thin* cases (a small, L << B)

$$L_\lambda(\lambda, L) = \int_0^L e_\lambda(\lambda, x)\, dx$$

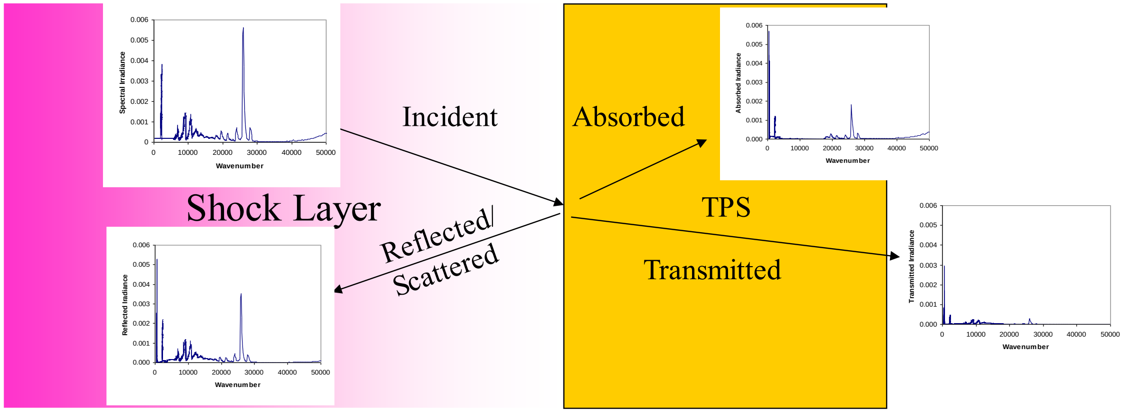
Spectral Radiance to Radiance

- Simply, the Radiance is the integral of the Spectral Radiance:

$$L = \int_{0}^{\infty} L_{\lambda}(\lambda)\,d\lambda$$

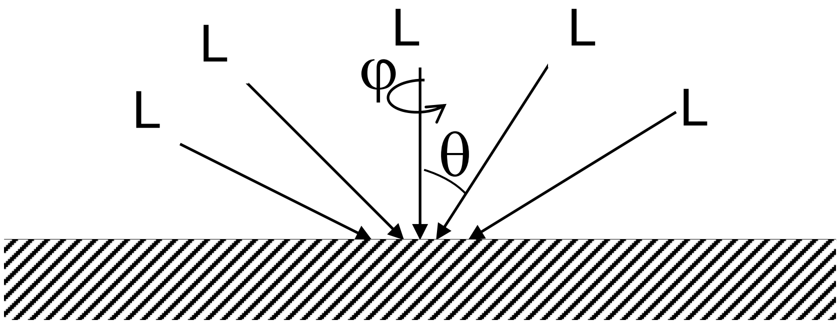


- However, heat absorbed depends on the interaction of the material with the radiation:



Radiation Comes From All Directions

- The (spectral) irradiance to a surface is the integral of the normal component of *(spectral) radiance*:



$$E_\lambda = \iint L_\lambda(\theta,\phi)\cos\theta\sin\theta\; d\theta d\phi$$

- Technically, the absorption/reflection coefficients are also functions of θ
- The integrations over wavelength and angle can (generally) be performed in any order

$$q_{rad} = \iiint \alpha(\lambda,\theta) L_\lambda(\lambda,\theta,\phi)\sin\theta\cos\theta\; d\lambda d\phi d\theta$$

Terminology

Quantity	Symbol	Units	Notes
Radiant energy	Q_e	J	energy
Radiant flux	Φ_e	W	radiant energy per unit time, also called *radiant power*.
Spectral power	$\Phi_{e\lambda}$	$W \cdot m^{-1}$	radiant power per wavelength.
Radiant intensity	I_e	$W \cdot sr^{-1}$	power per unit solid angle.
Spectral intensity	$I_{e\lambda}$	$W \cdot sr^{-1} \cdot m^{-1}$	radiant intensity per wavelength.
Radiance	L_e	$W \cdot sr^{-1} \cdot m^{-2}$	power per unit solid angle per unit *projected* source area.
Spectral radiance	$L_{e\lambda}$	$W \cdot sr^{-1} \cdot m^{-3}$	Radiance per wavelength, commonly measured in $W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}$ May also be expressed in terms of wavenumber or frequency.
Irradiance	E_e	$W \cdot m^{-2}$	power incident on a surface, also called *radiant flux density*.
Spectral irradiance	$E_{e\lambda}$	$W \cdot m^{-3}$	Irradiance per wavelength commonly measured in $W \cdot m^{-2} \cdot nm^{-1}$ May also be expressed in terms of wavenumber or frequency
Radiant exitance /emittance	M_e	$W \cdot m^{-2}$	power emitted from a surface.
Radiosity	J_e or $J_{e\lambda}$	$W \cdot m^{-2}$	emitted plus reflected power leaving a surface.
Radiant exposure	H_e	$J \cdot m^{-2}$	
Radiant energy density	ω_e	$J \cdot m^{-3}$	
Volumetric Radiance	ε	$W \cdot sr^{-1} \cdot m^{-3}$	power per unit solid angle per unit *volume.*
Volumetric Spectral Radiance	E_λ	$W \cdot sr^{-1} \cdot m^{-4}$	Volumetric Radiance per unit wavelength/frequency/wavenumber
Luminance	L_v	Cd/m^2	Radiance corrected for spectral response of the human eye
Luminous Power, Illuminance, Luminosity, etc.			Spectral Power, Irradiance, Radiosity, etc. corrected for response of the human eye

Adapted from http://en.wikipedia.org/wiki/Radianc

Intensity

The *radiance* ($\mathrm{W \cdot sr^{-1} \cdot m^{-2}}$) is sometimes called the *Intensity*

The *irradiance* ($\mathrm{W \cdot m^{-2}}$) is sometimes also called the *Intensity*

There is also something called the *radiant intensity* ($\mathrm{W \cdot sr^{-1}}$) that is different from intensity, but may also be called the *Intensity*

The *spectral radiant intensity* ($\mathrm{W \cdot sr^{-1} \cdot nm^{-1}}$) is often called the *spectral intensity* or *intensity*

The spectral *radiance* ($\mathrm{W \cdot sr^{-1} \cdot m^{-2}}$) is sometimes called the *spectral intensity* or *intensity*

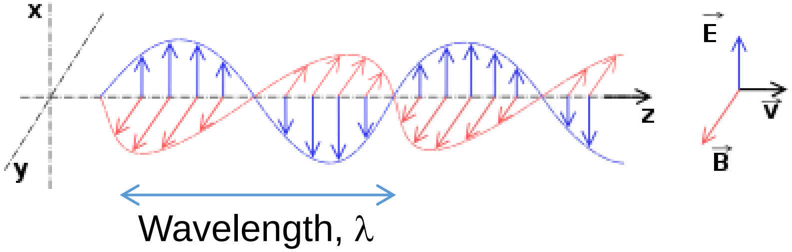
The *irradiance* ($\mathrm{W \cdot m^{-2}}$) is sometimes also called the *spectral intensity* or *intensity*

There are other quantities that might also be called intensity which are different from the above

Intensity is what people say when they don’t know or care what they are actually reporting

Wavelength, the 5th Dimension

- In the flowfield, the volumetric spectral radiance is a function of position and time (4 dimension)
- Radiation consists of electromagnetic waves (i.e. light)



- An electromagnetic wave is characterized by a wavelength
- Waves of different wavelength don’t (in general) interact with each other, so must be solved independently. This adds another dimension to radiation solutions
- The energy of the radiation is determined by its wavelength, which is also related to the frequency or the wavenumber

$E = hc/\lambda$ $\qquad$ $\nu = c/\lambda$ $\qquad$ $\bar{\upsilon} = 1/\lambda$

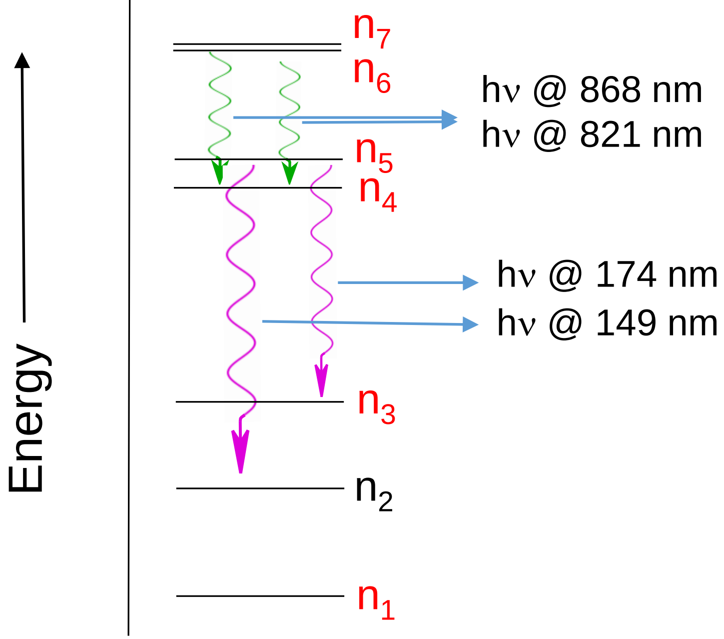
Energy (eV) $\quad$ Wavelength (nm) $\quad$ Frequency (Hz) $\quad$ Wavenumber (cm^{-1})

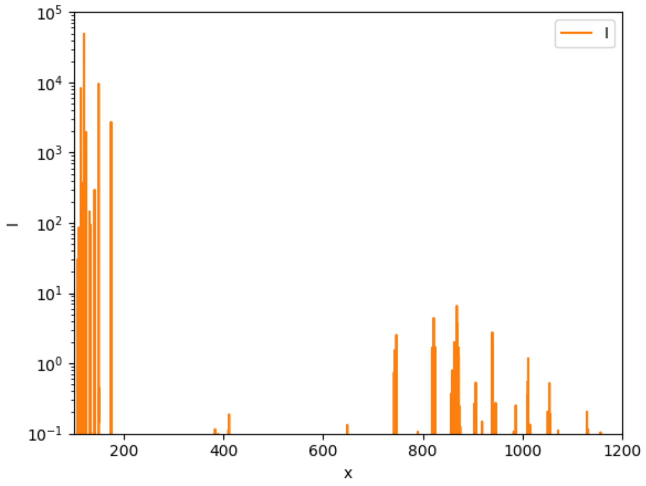
- Waves also have a polarization, but we’ll ignore that (assume randomly distributed, or circular)

Computing Emission Coefficients

- Emission coefficients depend on the species present in the gas
- Through the magic of quantum mechanics, each species has particular allowed energy states
- Transitions between allowed energy states cause radiation

Example: N atoms





Einstein coefficient(s^{-1})

Lineshape function (nm^{-1})

$$e_{174}(\lambda) = \frac{1}{2\pi}\,\frac{hc}{\lambda}\,A n_5 \phi(\lambda - 174.514)$$

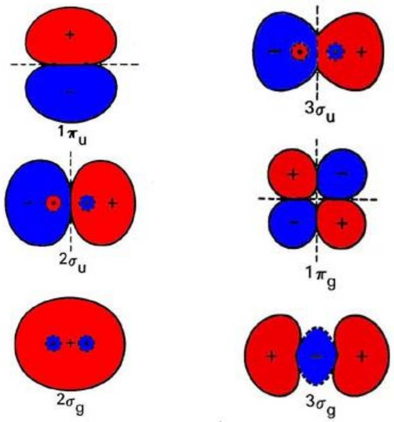
Density of upper state (cm^{-3})

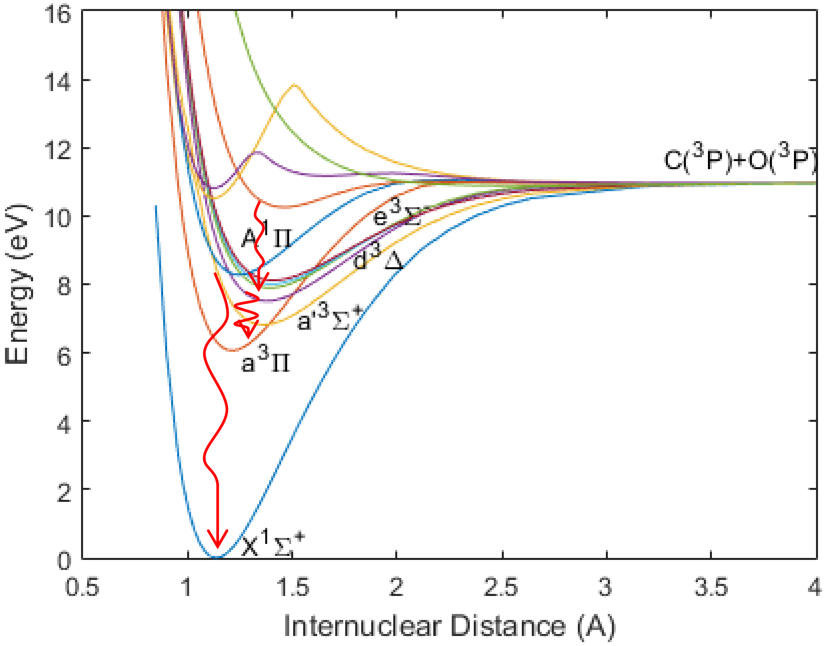
per unit solid angle, sr^{-1}

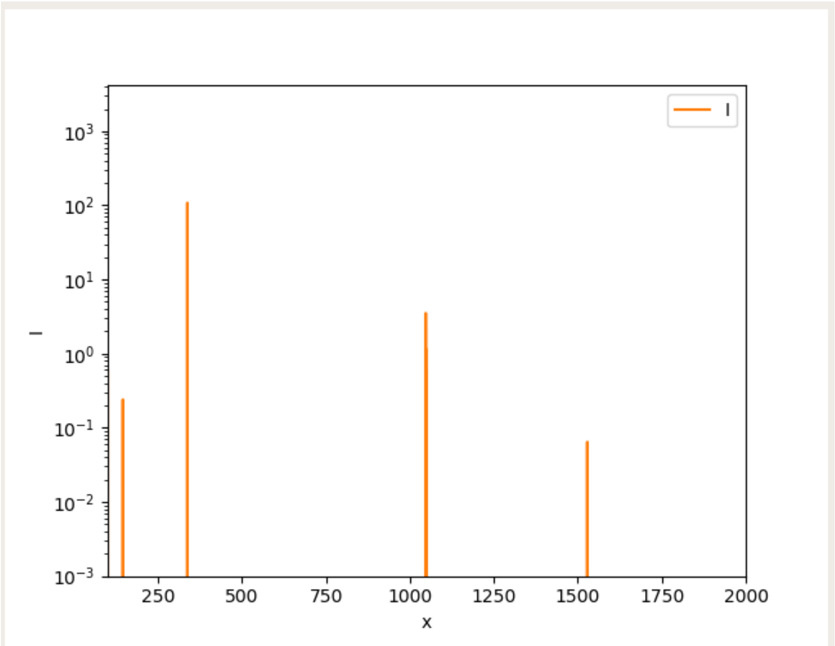
Energy of photon (J)

Molecular emission coefficients

- Molecules have more states
  - Electronic states

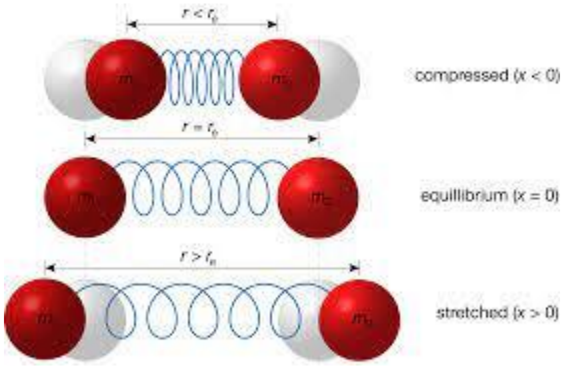


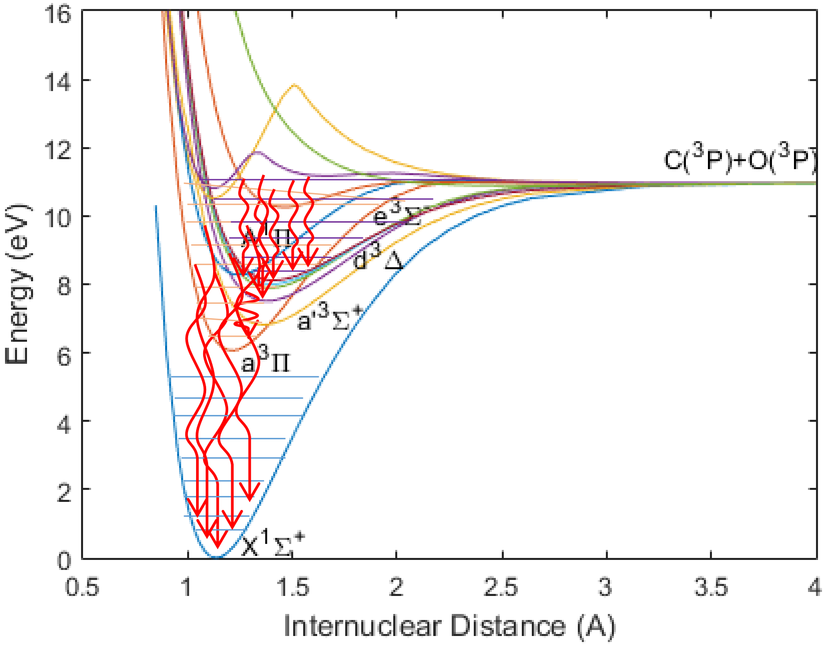


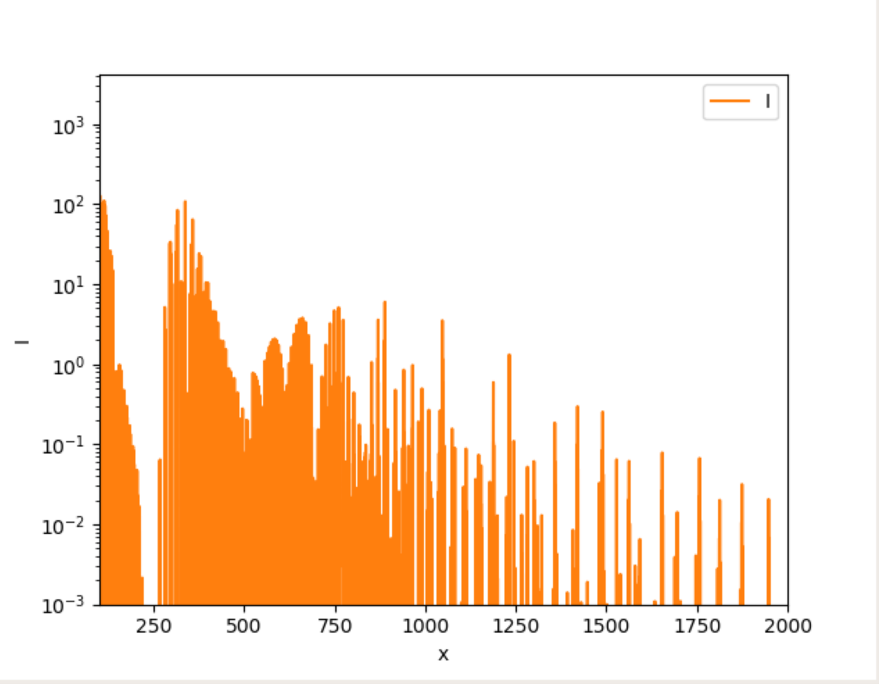


Molecular emission coefficients

- Molecules have more states
  - Electronic states
  - Vibrational states

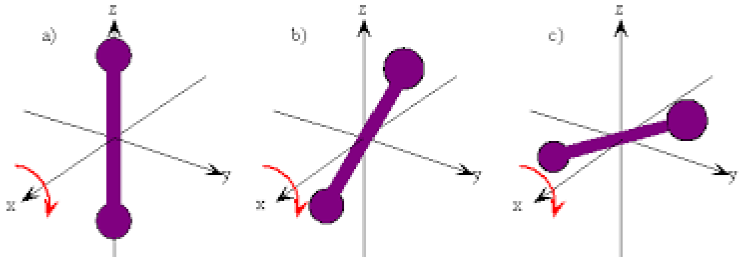


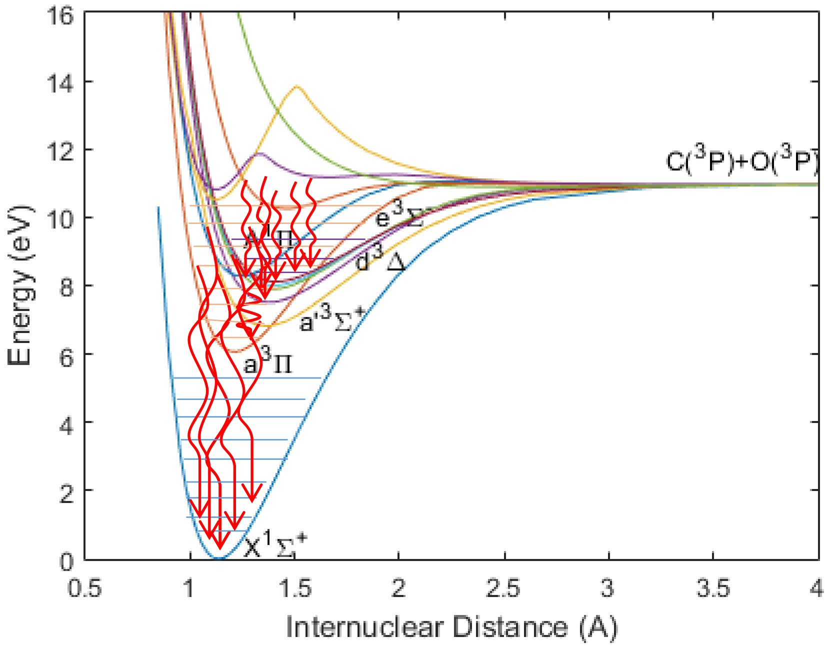


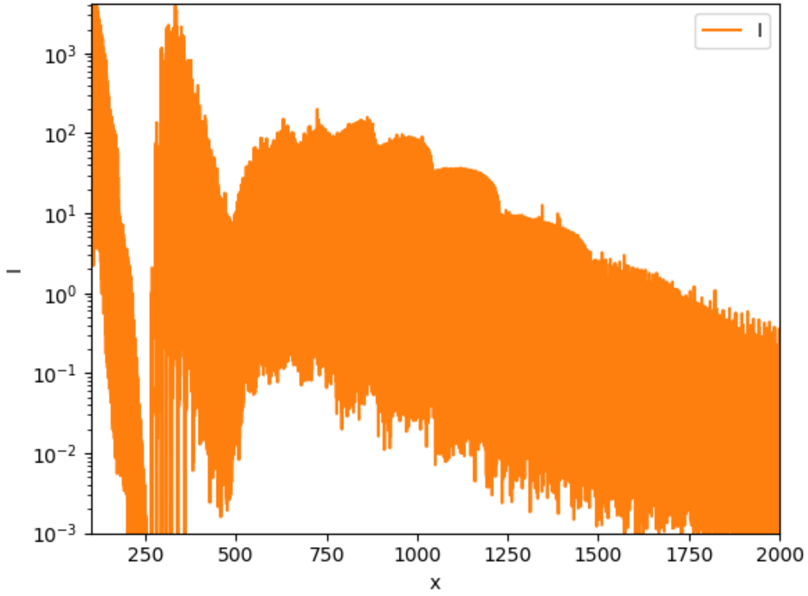


Molecular emission coefficients

- Molecules have more states
  - Electronic states
  - Vibrational states
  - Rotational states

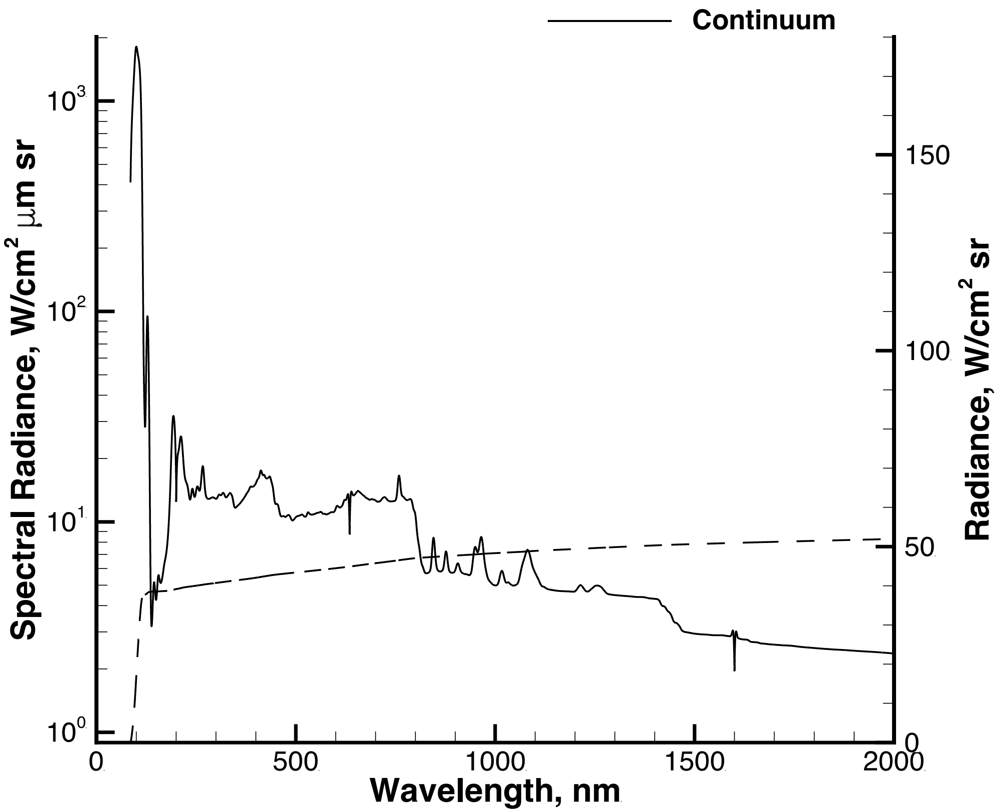






Building a spectrum

Example: FIRE II (Air entry, 10.7 km/s)



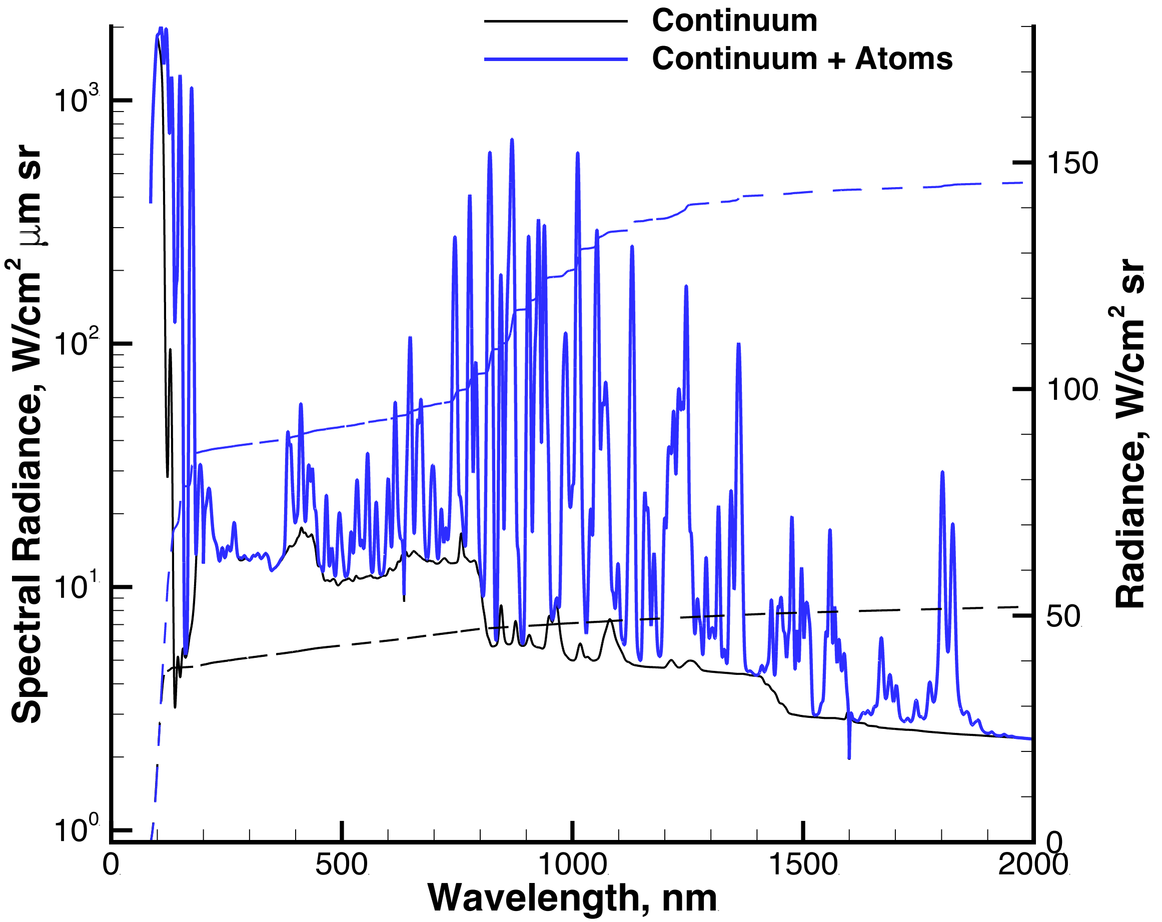
Continuum radiation, e.g.:

$$N^+ + e^- \rightarrow N + h\nu \qquad h\nu = \Delta E = E_e - \Delta E_{rxn}$$

Electron (kinetic) energy is not quantized – emits as a continuum

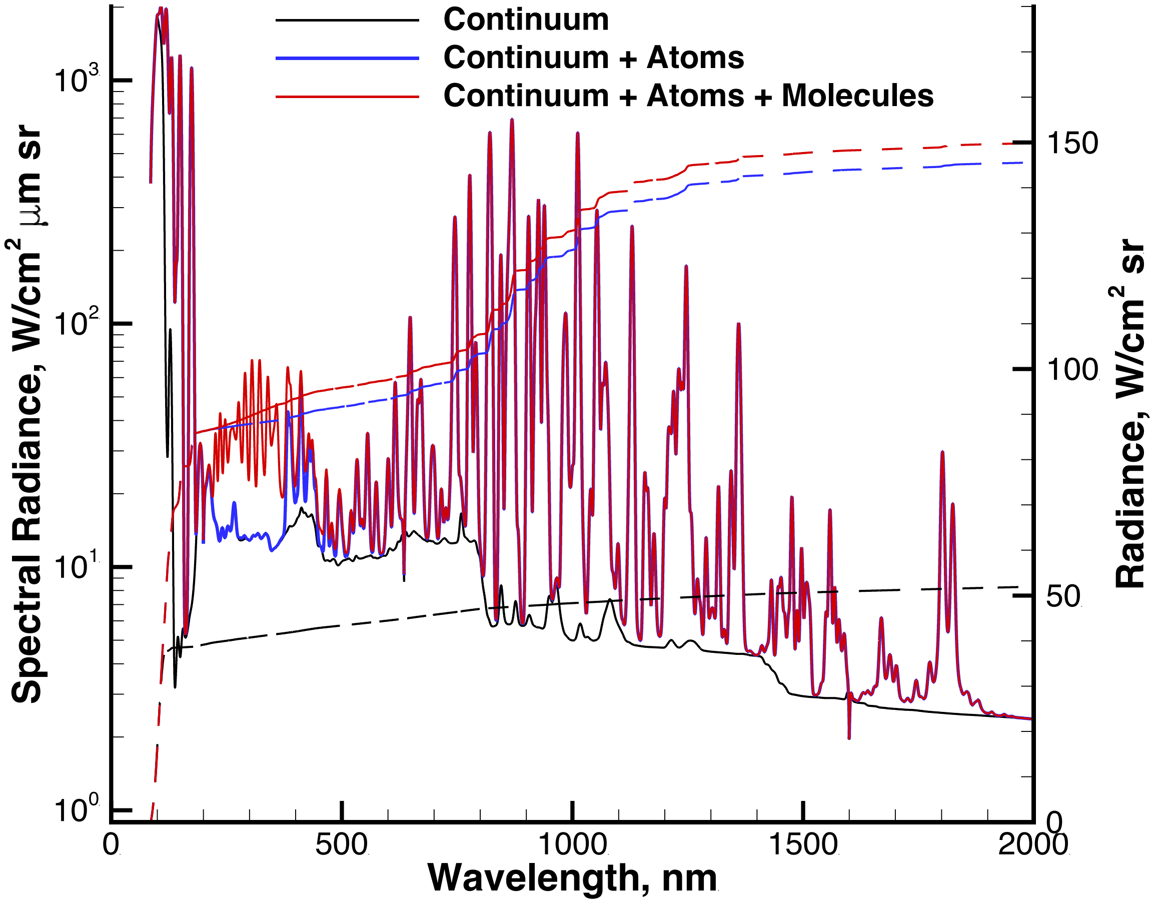
Building a Spectrum

FIRE II Test Case



Building a Spectrum

FIRE II Test Case



Solving state populations

- The density of flowfield species (from CFD) need to be converted to the density of excited states

$$e(\lambda)=\frac{1}{2\pi}\frac{hc}{\lambda}An_u\phi(\Delta\lambda)$$

- Boltzmann (thermal) distribution:

$$n_u=n_s\frac{g_u\exp\left(-E_u/kT\right)}{q_s}$$

- 4-Temperature (T_t,T_r,T_v,T_e) Boltzmann distribution

$$n_u=n_s\frac{g_e g_v g_r\exp\left(-E_e/kT_e\right)\exp\left(-E_v/kT_v\right)\exp\left(-E_r/kT_r\right)}{q_s(T_r,T_v,T_e)}$$

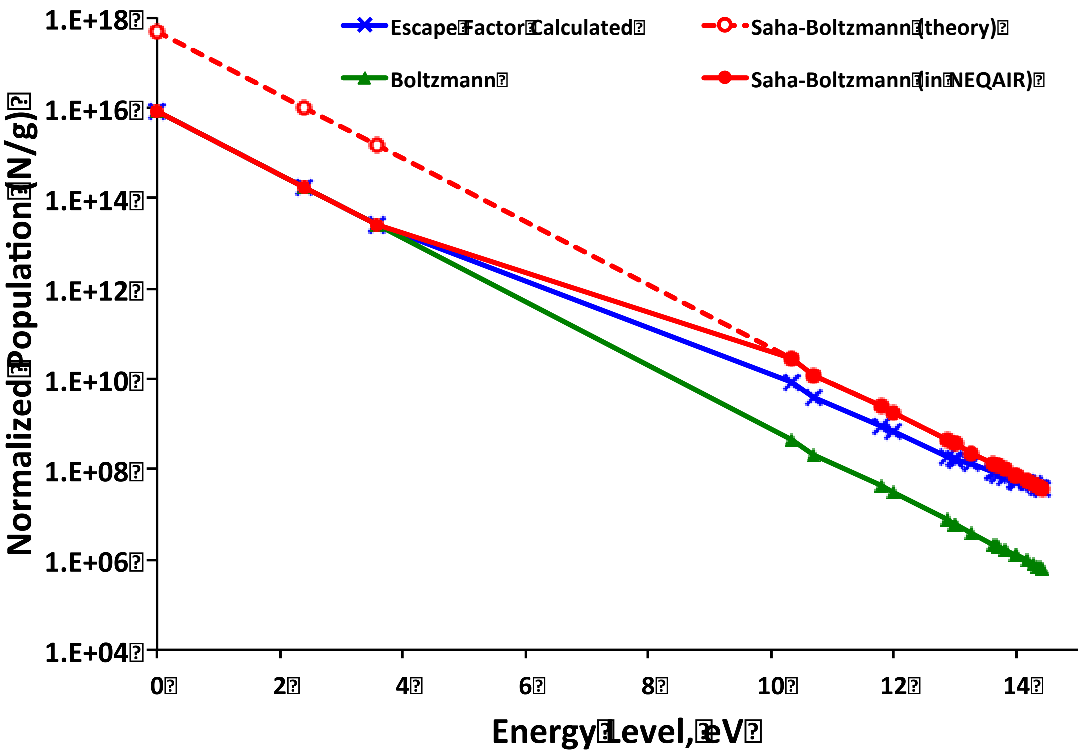
- Non-Boltzmann (non-thermal) distribution

$$\frac{dn_i}{dt}=\sum_j\left(k_{ji}^M n_M+k_{ji}^e n_e+B_{ji}\int\phi_{ji}(\lambda)I(\lambda)\right)n_j-\left(k_{ij}^M n_M+k_{ij}^e n_e+B_{ij}\int\phi_{ij}(\lambda)I(\lambda)\right)n_i+\sum_{j>i}A_{ji}n_j-\sum_{i>j}A_{ij}n_i+\sum_k r_k^i-r_{-k}^i n_i$$

Collisional excitation (heavy/electron) Absorption/Stim.Emission Spont.Emission State-specific reactions

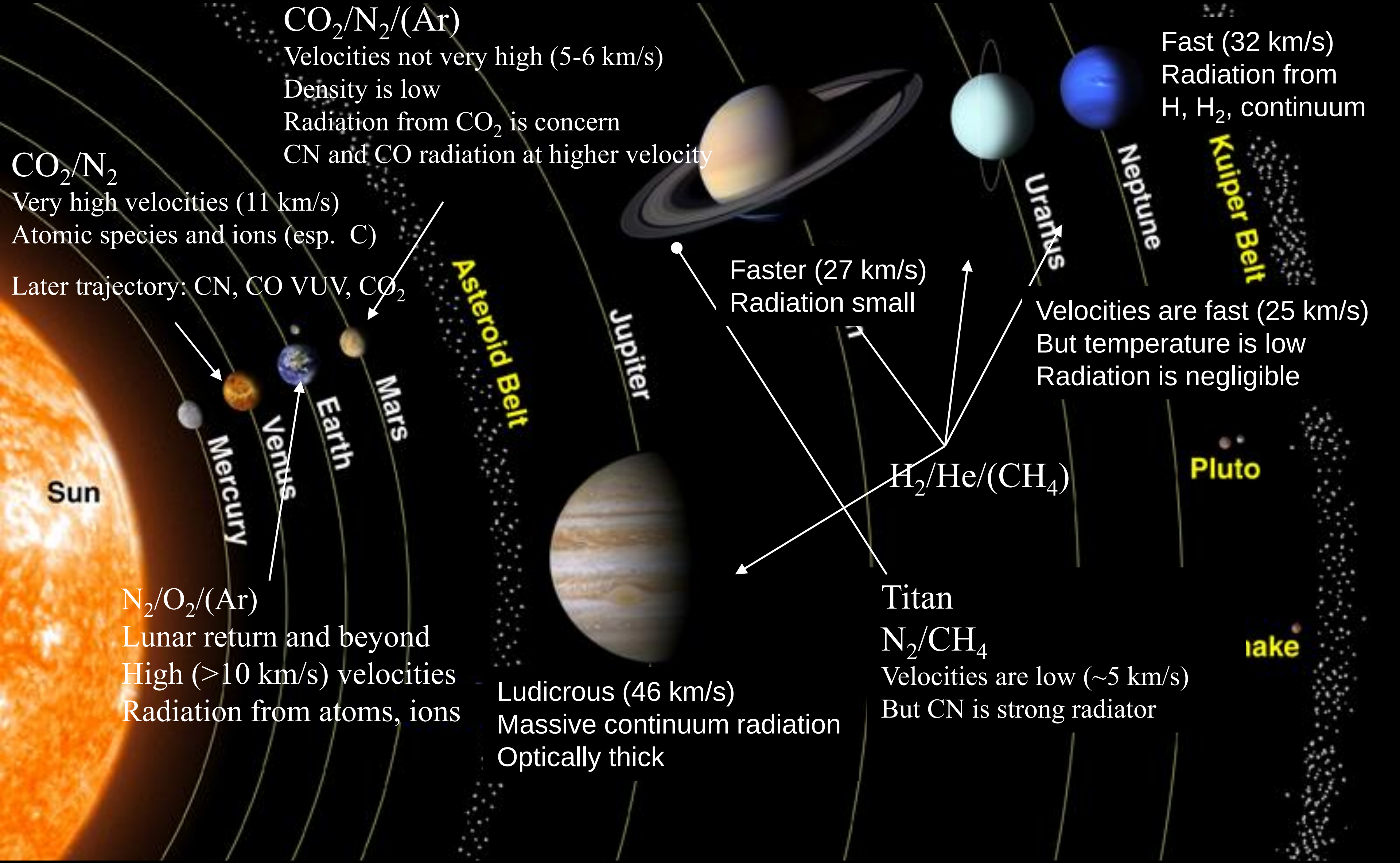
- Typically, it is necessary to solve non-Boltzmann in electronic modes. Rotational, vibrational modes close to thermal

State populations: Boltzmann Plot



- Boltzmann plot
  - Population/Degeneracy is log-linear w.r.t energy at Boltzmann
  - For molecules, need to normalize by $q_{vr}(T_v, T_r)$
  - Slope equals $1/T_e$
- Some states tend to equilibrate with electrons instead of the ground state (Saha)
- For molecules, may equilibrate with atoms or other species

Radiation concerns for Different Destinations



CO_2/N_2
Very high velocities (11 km/s)
Atomic species and ions (esp. C)

Later trajectory: CN, CO VUV, CO_2

$CO_2/N_2/(Ar)$
Velocities not very high (5-6 km/s)
Density is low
Radiation from CO_2 is concern
CN and CO radiation at higher velocity

$N_2/O_2/(Ar)$
Lunar return and beyond
High (>10 km/s) velocities
Radiation from atoms, ions

Ludicrous (46 km/s)
Massive continuum radiation
Optically thick

Faster (27 km/s)
Radiation small

$H_2/He/(CH_4)$

Velocities are fast (25 km/s)
But temperature is low
Radiation is negligible

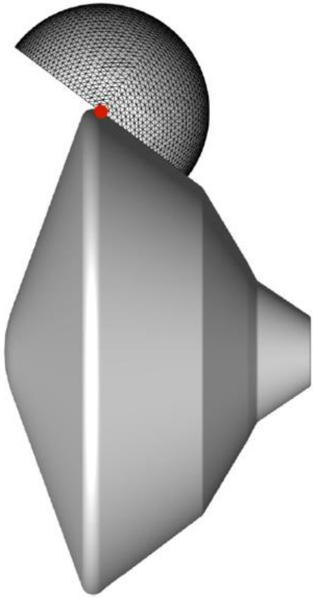
Fast (32 km/s)
Radiation from
H, H_2, continuum

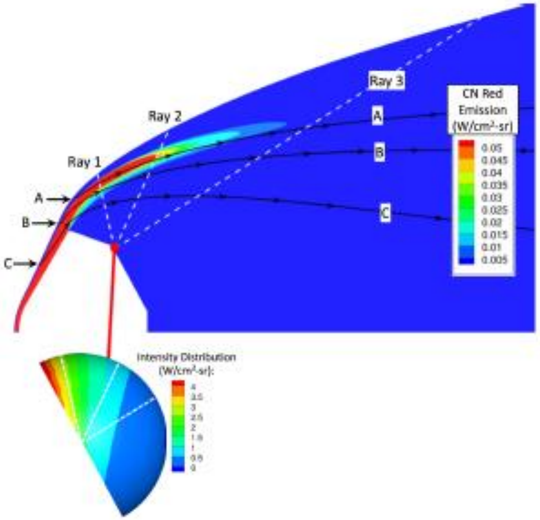
Titan
N_2/CH_4
Velocities are low (~5 km/s)
But CN is strong radiator

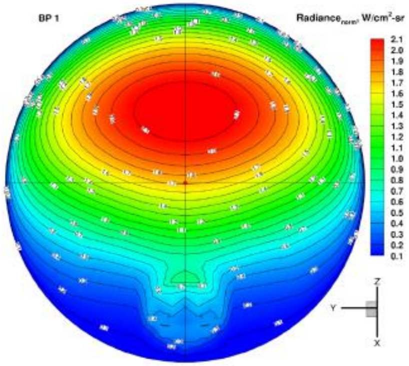
Evaluating the Angular Integral

- The hard (accurate) way :
  - Ray tracing
  - Full angular integration

$$E_\lambda = \iint L_\lambda(\theta,\phi)\cos\theta\sin\theta\, d\theta d\phi$$



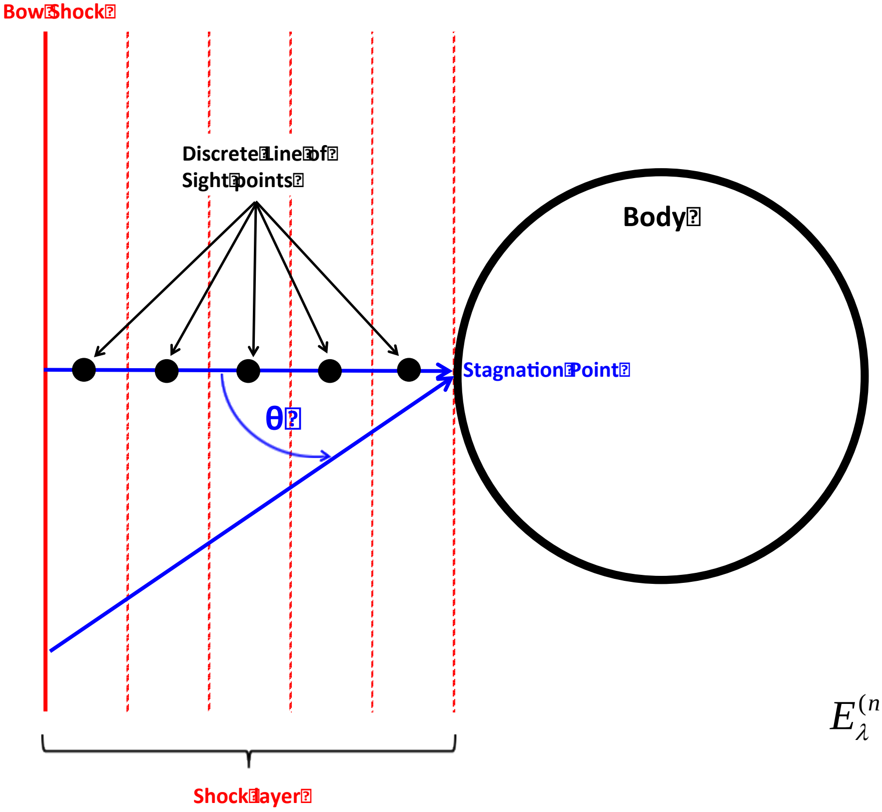




- Brute force approaches:
  - Evaluation of 100s-1000s of lines of sight
  - Can be slow
- Other approaches: Monte Carlo, Finite Volume
  - Not covered this talk

Tangent Slab Approximation

- Assume 1-D Semi-infinite geometry:



$$E_\lambda = \iint L_\lambda(\theta,\phi)\cos\theta\sin\theta\, d\theta d\phi$$

$$E_\lambda = 2\pi\int L_\lambda(\theta)\cos\theta\sin\theta\, d\theta$$

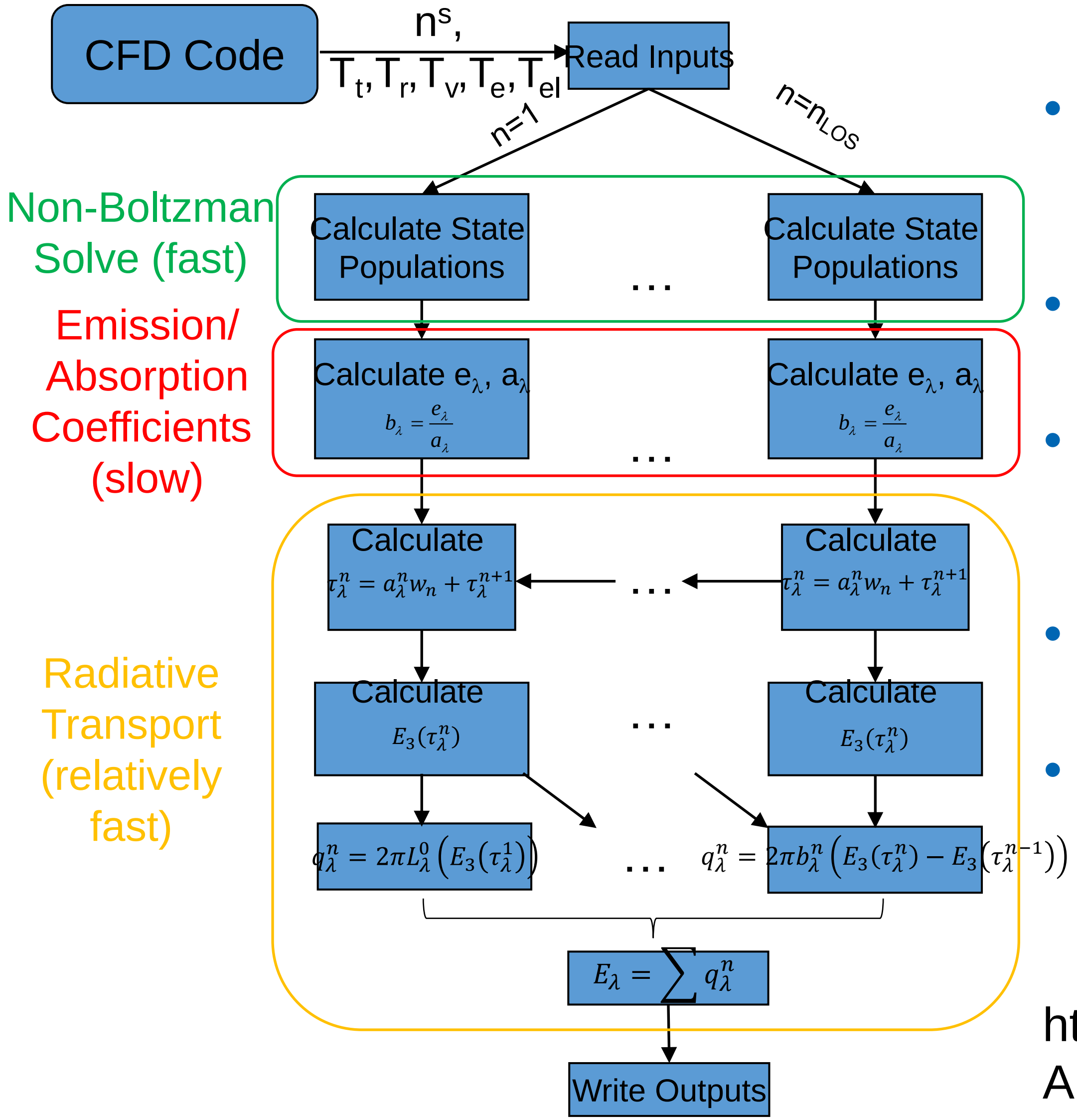
$$L_\lambda^n(\theta) = \frac{e_\lambda^n}{a_\lambda^n} + \left(L_\lambda^{n-1}(\theta) - \frac{e_\lambda^n}{a_\lambda^n}\right) e^{-a_\lambda^n w_n / \cos\theta}$$

$$\vdots$$

$$E_\lambda^{(n)} = 2\pi\left[L_\lambda^{(0)} E_3\left(\tau_\lambda^{(0,n)}\right) + \sum_{j=1}^{n} b_\lambda^{(j)}\left(E_3\left(\tau_\lambda^{(j,n)}\right) - E_3\left(\tau_\lambda^{(j-1,n)}\right)\right)\right]$$

- Integral may now be expressed as a 1-D integral, or a summation of transcendental functions.
- Only one Line of Sight required
- Limits: E/L = π (optically thick) to 2π (optically thin)
- Good on the forebody to ~10%. Worse on shoulder, bad on backshell

Putting it all together: radiative codes



CFD Code

n^s, $T_t, T_r, T_v, T_e, T_{el}$

Read Inputs

n=1

$n=n_{LOS}$

Non-Boltzman Solve (fast)

Calculate State Populations … Calculate State Populations

Emission/ Absorption Coefficients (slow)

Calculate e_λ, a_λ $b_\lambda = \frac{e_\lambda}{a_\lambda}$ … Calculate e_λ, a_λ $b_\lambda = \frac{e_\lambda}{a_\lambda}$

Radiative Transport (relatively fast)

Calculate $\tau_\lambda^n = a_\lambda^n w_n + \tau_\lambda^{n+1}$ … Calculate $\tau_\lambda^n = a_\lambda^n w_n + \tau_\lambda^{n+1}$

Calculate $E_3(\tau_\lambda^n)$ … Calculate $E_3(\tau_\lambda^n)$

$q_\lambda^n = 2\pi L_\lambda^0 \left(E_3(\tau_\lambda^1)\right)$ … $q_\lambda^n = 2\pi b_\lambda^n \left(E_3(\tau_\lambda^n) - E_3(\tau_\lambda^{n-1})\right)$

$E_\lambda = \sum q_\lambda^n$

Write Outputs

- NASA has two codes
  - NEQAIR (Ames Research Center)
  - HARA (Langley Research Center)
- JAXA, ESA, ROSCOSMOS have their own codes
- Several academic codes exist with varying levels of fidelity/options
- HARA is packaged with LAURA CFD code. US release only.
- NEQAIR is available for US and foreign release. Has pretty wide use through the scientific and engineering community:

https://software.nasa.gov/software/ARC-15262-1B

Conclusions

- Regions of relevance for radiative heating
  - Important at High velocity, high density
  - More important on Large vehicles
  - Often important on the backshell
  - Sometimes radiation surprises us (e.g. Mars backshell heating by CO_2)
- Radiative Heat flux is an integral over solid angle, wavelength, linear distance
  - The fundamental measure of radiation is the emission coefficient, or volumetric spectral radiance
- Radiation depends on wavelength – so does your TPS and sensors
- Some radiation terminology and concepts to remember:
  - Optical thickness
  - Relationship of absorption to emission (blackbody fn)
  - Radiance vs. Irradiance and Intensity
  - Tangent slab vs. 3D radiation
  - Molecular vs. Atomic vs. Continuum Radiation
  - Boltzmann/non-Boltzmann
  - Line of Sight
  - Emission and absorption coefficients
- Advanced topics not covered
  - Escape factor and non-local effect
  - Radiation/flowfield coupling
  - Line broadening
  - Excited state chemistry
  - Spectral parameters
  - The Planck Function
  - Relationship of Boltzmann distribution to Planck’s function
  - QSS Approximation
  - Wavelength Classifications (vacuum ultraviolet, mid-infrared)
  - Radiative Transport Equation